

U.S. ARMY CORPS OF ENGINEERS  
LOWER MISSISSIPPI VALLEY DIVISION

REPORT  
ON  
STANDARDIZATION OF RIPRAP GRADATIONS

NOVEMBER 1981  
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TABLE OF CONTENTS

	<u>Page</u>
Purpose	1
Scope	1
Background	1
Field Investigations	1
Riprap Design Analysis	3
Standardization of Riprap Gradations	5
Summary and Actions	8
References	9
Inclosures 1-6	

## REPORT ON STANDARDIZATION OF RIPRAP GRADATIONS

1. Purpose. This report on standardization of riprap gradations is prepared in response to comments made by the Associated General Contractors (AGC) meeting on specifications held in Biloxi, Mississippi, on 29 January 1981 (Inclosure 1). The Lower Mississippi Valley Division (LMVD) concurred with AGC that it was desirable to develop standard gradations for riprap at and adjacent to structures, and agreed to make a study to determine the cost effectiveness within the design criteria for such special riprap.

2. Scope. The report addresses the capability of the quarries to produce various riprap gradations, and the sensitivity of changing gradations during a production cycle. It also provides a review of the design guidance and background information on their development. The economic solutions to all the problems associated with producing the riprap gradations, transporting the riprap, and meeting in-place gradation requirements are quite complex and beyond the scope of this study. However, several of these problems are discussed from the standpoint of the contractor, the quarry operator, and the designer in an effort to properly evaluate the impact of riprap standardization. Finally, areas where standardization can be accomplished are identified and actions to be taken for implementation are outlined. Design and gradation of riprap for wave-wash protection on earth embankments and construction of river dikes are beyond the scope of the study; therefore, this report does not address the gradation of graded stone A, B, or C or "stone bank paving," all of which are used extensively in the Channel Improvement Program on the main stem Mississippi River.

3. Background. General guidance for the design of riprap to be used at U. S. Army Corps of Engineers (Corps) structures and channels is provided in Engineer Technical Letter (ETL) 1110-2-120<sup>1</sup>, Engineer Manual (EM) 1110-2-1601<sup>2</sup>, and Hydraulic Design Criteria (HDC) 712-1<sup>3</sup>. These criteria specify methods that are to be used in establishing the minimum 50 percent lighter by weight ( $W_{50}$ ) of a stable layer of graded stone riprap for the hydrodynamic forces to which it will be subjected. From this mean weight, the stone gradation and layer thickness are established through specified relationships, depending on the specific gravity of the stone and the degree of flow turbulence expected at the job site. Rather than specifying a single gradation, a gradation band is established that is intended to provide some latitude in the gradation of stone produced in the quarry and delivered to the job site.

#### 4. Field Investigations.

a. During the course of this study six quarries that produce riprap were visited and one other was contacted by telephone to gain first-hand knowledge on quarry operations and discuss the various aspects of riprap production. Quarry managers were queried with respect to production capabilities, costs of changing machinery to produce different gradations, and problems related to producing the gradation bands presently being used. The visits also allowed the quarry managers the opportunity to ask about the different gradation curves and the reason for the curves overlapping in some cases. The following paragraphs summarize these discussions as they relate to riprap gradations specified for Corps projects.

b. A major concern of the rock quarry managers during the past few years has been the increasing number of different gradation curves specified for riprap production. Those interviewed all felt that the number of different gradations being requested was increasing. One quarry manager stated that he had received a set of specifications which called for two separate riprap gradations, with the two gradation curves having the same maximum and minimum 100 percent lighter by weight ( $W_{100}$ ); and minimum 15 percent lighter by weight ( $W_{15}$ ) size. The quarry manager further stated that the two gradations would have required two separate sets of screens to produce, however, the final product would have looked the same. The two sets of curves as originally specified are shown on Inclosure 2. The District requesting the stone did change the specifications to one common gradation.

c. Production rates of graded stone were found to vary considerably between the quarries visited, with the production rate being a function of the shot pattern, type of stone being produced, type of machinery being used to grade stone, and the gradation of the stone being produced. Most of the quarries have their operation set up to produce the graded stone first after it passes through the grizzly and over the lower size screen. Stone falling outside the gradation band is then used to produce other crushed stone and aggregate. Normally, this means that when the grizzly and screens are changed to produce a different gradation of stone, the total production has to shut down. Managers of the larger quarries generally agreed that total stone production would usually average about 1,200 tons per hour and of the total, the production of graded stone could vary from 100 tons to 500 tons per hour depending on the variables stated above. They generally agreed that making a change in the machinery required a shutdown of 6 to 10 hours. Some of the managers stated that in order for it to be cost effective to change their machinery to produce a special riprap gradation, an order of at least 1 week's production would be required. This would mean that small orders of graded stone would receive little or no interest from some of the quarries unless they had the stone stockpiled or expected another order of the same gradation in the immediate future. Quarry managers were asked if production costs varied with a change from smaller to larger stone gradations. There was no consensus of opinion, but most stated their total production rate would increase if they were producing the coarser gradations, however this required more screens to remove the greater amount of fines.

d. Selected sets of gradation curves covering the spectrum of gradations commonly used in LMVD was prepared and shown the quarry managers (Inclosures 3 and 4). They all stated this full range of gradation bands could be produced, however, they indicated that production cost would be increased due to the need for additional screens. While all managers were not in agreement, the consensus of opinion was that the gradation bands were too tight at the 50 percent lighter by weight point for the set of gradation curves shown them. Most also agreed they would prefer the band be opened on the coarser side rather than the finer side since there is a tendency for certain types of stone to break up and segregate during transit, resulting in a different gradation from that produced at the quarry. Since some gradation tests are run at the job site rather than at the quarry, they stated that some relaxation of the band width and amount of fines allowed would assist in meeting gradation requirements. There appeared to be some confusion among the quarry managers on the amount and size of fines allowed below the minimum 15 percent lighter by weight point ( $W_{15}$ ) of the specified gradation curves. Several of the quarry managers expressed concern over the lack of fines allowed below the minimum  $W_{15}$ , while at least one manager asked

specifically that 5 to 10 percent be allowed for fines below the minimum point. By definition, up to 15 percent of the total sample weight can weigh below the minimum  $W_{15}$  stone weight. However, guidance furnished in EM 1110-2-1601 for establishing the allowed volume of fines states that, "the bulk volume of stone lighter than the  $W_{15}$  stone should not exceed the volume of voids in revetment without this lighter stone." Therefore, the amount of fines should be kept to the minimum practical to be consistent with good riprap production practices and handling procedures. Quarry producers, as well as Corps inspectors, should be aware that small amounts of fines are acceptable.

#### 5. Riprap Design Analysis.

a. A review of the design criteria presently being used in LMVD to size riprap and specify gradation and layer thickness was made during this study in order to determine if any standardization in design could be accomplished. The basic riprap design criteria being used to size riprap compare favorably to preliminary results of recent Waterways Experiment Station (WES) hydraulic model studies<sup>4</sup> on riprap stability. The gradation curves furnished in ETL 1110-2-120 allow for some relaxation in the maximum 50 and 15 percent lighter by weight points, which would result in a wider band as requested by quarry managers. The resistance of riprap layers to tractive forces would not be affected by this change. The following is a summary of the design guidance presently being used.

(1) Since 1970 the Corps has used riprap design guidance based on Isbach's equation for movement of stone in flowing water. This guidance was published in HDC 712-1 and has been used to design riprap sizes for channel bottoms and side slopes downstream from stilling basins, river closures, and flood control channels. The Isbach coefficient of 0.86 recommended for sizing riprap for use in high-turbulence flow areas downstream of stilling basins and a coefficient of 1.20 was recommended for use in sizing riprap for low-turbulence flow areas such as flood control channels. Guidance furnished in the above referenced publication stated that the lower limit of the  $W_{50}$  stone should not be less than the weight of stone determined using the Isbach equation.

$$V = C \left\{ 2g \frac{\gamma_s - \gamma_w}{\gamma_w} \right\}^{\frac{1}{2}} (D_{50})^{\frac{1}{2}}$$

where:

V = Velocity (Average)  
C = Isbach coefficient  
g = Acceleration of gravity ft/sec<sup>2</sup>  
 $\gamma_s$  = Specified weight of stone, lb/ft<sup>3</sup>  
 $\gamma_w$  = Specified weight of water: lb/ft<sup>3</sup>  
D = Stone diameter, ft, where the diameter of a spherical stone in terms of its weight W is:

$$D = \left( \frac{6W_{5C}}{\pi \gamma_s} \right)^{1/3}$$

(2) The thickness of the riprap blanket and the gradation are interrelated. Depending on where the riprap will be placed, the thickness of the riprap layer specified will vary from 1.0 to 1.5 times the maximum  $D_{100}$  stone size in the gradation. Miscellaneous Paper No. 2-777<sup>5</sup> discusses this

relationship and points out that with a broad size span of riprap gradation, isolated pieces of large rock could protrude into the flow unless sufficient layer thickness is provided. The flow will accelerate around the large stone and remove smaller pieces, creating pockets where turbulence is intensified. Therefore, the layer thickness should be increased to 1.5 times the maximum  $D_{100}$  stone size in high-turbulence areas, such as around stilling basins, in order to ensure the larger pieces are inbedded properly. In low-turbulence flow areas the layer thickness can be reduced to the diameter of the largest stone in the gradation band. A nominal increase (50 percent) in layer thickness for underwater placement is normal to assure minimum layer thickness. Guidance furnished in EM 1110-2-1601 is used to compute the shear forces on riprap layers on both channel bottom and side slopes. The following is a summary of the guidance furnished in EM 1110-2-1601 and ETL 1110-2-120 for determining riprap gradation and thickness.

(a) Stone Gradation. The gradation of stones in riprap revetment affects the riprap's resistance to erosion. The stone should be reasonably well graded throughout the in-place layer thickness. Specifications should provide for two limiting gradation curves, and any stone gradation as determined from a field test sample, that lies within these limits should be acceptable. The gradation limits should not be so restrictive that stone production costs would be excessive. The choice of limits also depends on the underlying filter requirements if a graded stone filter is used. The following criteria provide guidelines for establishing gradation limits.

The lower limit of  $W_{50}$  stone should not be less than the weight of stone required to withstand the design shear forces as determined by the procedure given in EM 1110-2-1601 and HDC 712-1.

The lower limit of  $W_{50}$  stone should not exceed: five times the lower limit of  $W_{50}$  stone, that size which can be obtained economically from the quarry, or that size which will satisfy layer thickness requirements specified in paragraph 5a(2)(b) below.

The lower limit of  $W_{100}$  stone should not be less than two times the lower limit of  $W_{50}$  stone.

The upper limit of  $W_{100}$  stone should not exceed: five times the lower limit of  $W_{50}$  stone, that size which can be obtained economically from the quarry, or that size which will satisfy layer thickness requirements specified in paragraph 5a(2)(b) below.

The lower limit of  $W_{15}$  stone should not be less than one-sixteenth the upper limit of  $W_{100}$  stone.

The upper limit of  $W_{15}$  stone should be less than the upper limit of the filter as determined using guidance in EM 1110-2-1601.

The bulk volume of stone lighter than the  $W_{15}$  stone should not exceed the volume of voids in revetment without this lighter stone.

$W_0$  to  $W_{25}$  stone limits may be used instead of  $W_{15}$  stone limits determined by the above criteria if desirable to better utilize available stone sizes.

(b) Riprap Layer Thickness. All stones should be contained reasonably well within the riprap layer thickness to provide maximum resistance against erosive forces. Oversize stones, even in isolated spots, may cause riprap failure by precluding mutual support between individual stones, providing large voids that expose filter and bedding materials, and creating excessive local turbulence that removes smaller stones. Small amounts of oversize stone should be removed individually and replaced with proper size stones. When a quarry produces a large amount of oversize stone, consideration should be given to changing the quarrying method, using a grizzly to remove the oversize stone, obtaining the stone from another source, or increasing the riprap layer thickness to contain the larger stone. The following criteria apply to the riprap layer thickness:

It should not be less than the spherical diameter of the upper limit  $W_{100}$  stone or less than 1.5 times the spherical diameter of the upper limit  $W_{50}$  stone, whichever results in the greater thickness.

It should not be less than 12 inches for practical placement.

The thickness determined by either method above should be increased by 50 percent when the riprap is placed underwater to provide for uncertainties associated with this type of placement.

An increase in thickness of 6 to 12 inches, accompanied by appropriate increase in stone size, should be provided where riprap revetment will be subject to attack by large floating debris or by waves from boat wakes, wind, and bed ripples or dunes.

b. The placement of riprap is also an important part of riprap design since the effectiveness of riprap layer can be decreased significantly if excessive segregation and breakage occur. This concern is addressed in EM 1110-2-1601 and is summarized as follows:

The common methods used to place riprap are hand placing; machine placing, such as from a slip, dragline, or some other form of bucket; and dumping from trucks and spreading by bulldozer. Hand placement produces the best riprap revetment, but it is the most expensive method except when stone is usually costly and/or labor unusually cheap. Hand placed riprap can be used on steeper side slopes than with other placing methods. This reduces the required volume of rock. However, the greater cost of hand placement usually makes machine or dump placement methods and flatter slopes more economical. Hand placement on steeper slopes should be considered when channel widths are constricted by existing bridge openings or other structures and when rights-of-way are costly, provided the steeper slopes satisfy the appropriate slope stability guidance. In the machine placement method, sufficiently small increments of stone should be released as close to their final positions as practical. Rehandling or dragging operations to smooth the revetment surface tend to result in segregation and breakage of stone and rough revetment surface. Stone should not be dropped from an excessive height as this may result in the same undesirable conditions. Riprap placement by dumping and spreading is the least desirable method as a large amount of segregation and breakage can occur. In some cases, it may be economical to increase the layer thickness and stone size somewhat to offset the shortcomings of this placement method.

6. Standardization of Riprap Gradations.

a. There are several areas in which the criteria can be modified to reduce the number of different gradations currently being used within the Corps. The most obvious is to establish a set of gradation limits for given design conditions and layer thickness, to avoid arbitrary differences resulting from "rounding" preferences. This action can and will be implemented within LMVD. Other actions that would result in a reduced number of gradations are:

(1) Increasing the incremental step between theoretical layer thicknesses from the 3- and 6-inch increments currently used.

(2) Reducing the number of different riprap designs by using oversized riprap in some areas to be protected rather than specifying different gradations and layer thicknesses for two or more areas to be protected.

(3) Selecting a single design value of specific weight for stone that is representative of quarries in the region, and still ensure the stone meets minimum standards.

(4) Eliminating the option of using a slightly open or closed gradation band at the upper limits of the  $D_{50}$  and  $D_{15}$  points and adopting only one set of gradation bands for given design conditions.

(5) Combining design gradations for low-turbulence and high-turbulence areas; i.e., gradations established that will meet low-turbulence design guidance with a set of layer thicknesses, and also meet high-turbulence design guidance with a correspondingly different set of layer thickness. Each of these actions is discussed in the following paragraphs.

b. Action 1. Constrained by the fact that the riprap must meet minimum guidance, "standardizing" gradations becomes primarily an economic consideration. Increasing the interval between layer thickness for a set of standard gradations would result in an oversized riprap with increased reliability, but would also require an increased volume of stone on some jobs. In these cases, added cost would result due to the increased volume of riprap to be produced at the quarry, and in transporting and placing the additional riprap at the construction site. The trade-off in production savings that may be obtained by not having to change the machinery to produce a smaller gradation may be offset by the added cost of the increased volume and layer thickness required for an oversized gradation. The design and materials engineer would be required to determine the trade-off for each job. The cost effectiveness of increasing the interval between gradation layer thickness versus using non-standard layers is difficult to analyze without knowing the quarry that will be used to supply the stone and the mode of transportation for moving the riprap from the quarry to the job site. If the quantity of stone is sufficiently large, increasing the thickness of the riprap layer in order to use a standard gradation would probably be more expensive than paying the extra unit production cost at the quarry necessary to produce the non-standard gradation riprap. Information provided by quarry managers which indicates that 1 week's production is normally required for an economical change in gradation should be helpful in making this



gradations. However, it is concluded that the 27-inch and 33-inch thick layers be deleted because the gradations have a high degree of overlap with adjacent layers, and they are not as commonly used as the 24-, 30-, and 36-inch layers.

c. Action (2). There are many examples where small quantities of several different riprap gradations are specified in a single contract. A good example would be where scour protection is required at several bridges, and each design indicates a different gradation. Good engineering practice requires the designer to consolidate the minimum number of different designs and accept an overdesigned job on some of the bridges in order to avoid the added cost of producing, transporting, stockpiling, and placing several different gradations of stone in small quantities.

d. Action (3). A study of practices within LMVD Districts indicates that several different specific weight values are being used in riprap design, resulting in different gradations being specified to meet the same design conditions. Since in the design stage the quarry that will supply the stone is unknown, this procedure has little merit. A more logical procedure would be to use the minimum specific weight for stone that normally meets other specified requirements such as abrasion, hardness, absorption, etc., and does not eliminate quarries from competition which are approved as supply sources. This weight has been determined to be a specific weight of 155 pounds per cubic foot.

e. Action (4). Design guidance now allows some latitude in establishing the upper weight limits for the gradation band at the  $W_{50}$  and  $W_{15}$  Points as discussed previously in paragraph 5 and shown on Inclosure 5 for a typical gradation. This was intended to provide the designer with flexibility in establishing the gradation band in order that varying degrees of control would be exercised depending on design conditions, anticipated problems in production; etc., as previously discussed. Based on the field visits and discussions with quarry managers, establishing standards at these points which specify the open gradation band is highly desirable. Since this is also acceptable from a design standpoint, it is concluded that the gradation bands be standardized to use only the open bands.

f. Action (5). As discussed in paragraph 5, the design of riprap for low--turbulence and high-turbulence flow areas differ only slightly, however, the layer thickness is increased in the latter case. An analysis of different design cases reveals that there are gradation bands that are essentially identical, although they represent entirely different design conditions. Slight adjustments in the gradation bands and an accompanying slight shift in layer thicknesses for the low-turbulence design would result in standardization of these bands and essentially eliminate half the possible number of gradations previously used. The table on Inclosure 6 shows the resulting standard gradations and layer thicknesses for both high- and low-turbulence designs that are to be used. Gradations shown are the slightly opened bands as discussed in paragraph e above.

## 7. Summary and Actions.

a. This report has addressed several steps that can and will be taken to standardize riprap gradations and reduce the number of gradations currently in use. The report also reviewed design criteria and quarry operations in relation to the production of this riprap. The investigation revealed that there was some misunderstanding of gradation bands, particularly with regard to the smaller

stone. Mutual understanding of the gradation bands is needed among quarry managers, contractors, and Government inspectors. It was also found that quarries capable of producing graded riprap could produce almost any gradation specified. However, there are inherent cost savings and increased efficiency associated with using standard gradations that quarries have experience in producing, and keeping the number of gradations to the minimum practical. An analysis of cost versus production indicates that this is not necessarily an overriding factor, but does lend merit to establishing a set of standardized gradations. It is concluded that the almost unlimited number of gradations currently in use should be reduced to eight machine produced gradations. This will provide economy in construction and still retain sufficient flexibility for design.

b. The conclusions summarized below, which ensure safety and economy in design, will be implemented by the LMVD Districts.

(1) Use the standardized gradations shown on Inclosure 6 for specifying riprap at hydraulic structures and in channels adjacent thereto. Both low- and high-turbulence design gradations are included. There may be isolated cases where the use of a non-standard gradation is appropriate and can be justified as cost effective.

(2) Use oversized stone when cost effective, in order to reduce the number of gradations required in a contract involving several small placements.

(3) Use a specific weight of 155 pounds per cubic foot for all riprap design in order to prevent small gradation differences for the same design conditions.

(4) Use the increased maximum  $W_{50}$  and  $W_{15}$  points on the gradation curve (open hand) as shown in Inclosure 6 for both low- and high-turbulence flow conditions.

References

<sup>1</sup>Engineering Technical Letter No. 1110-2-120, dated 14 May 1971

<sup>2</sup>Engineering Manual 1110-2-1601, dated 1 July 1970

<sup>3</sup>Hydraulic Design Criteria, sheet 712-1, dated September 1970

<sup>4</sup>Ongoing WES Research and Development Program, 31028, Title: Effects of Water Flow on Riprap in Flood Channels.

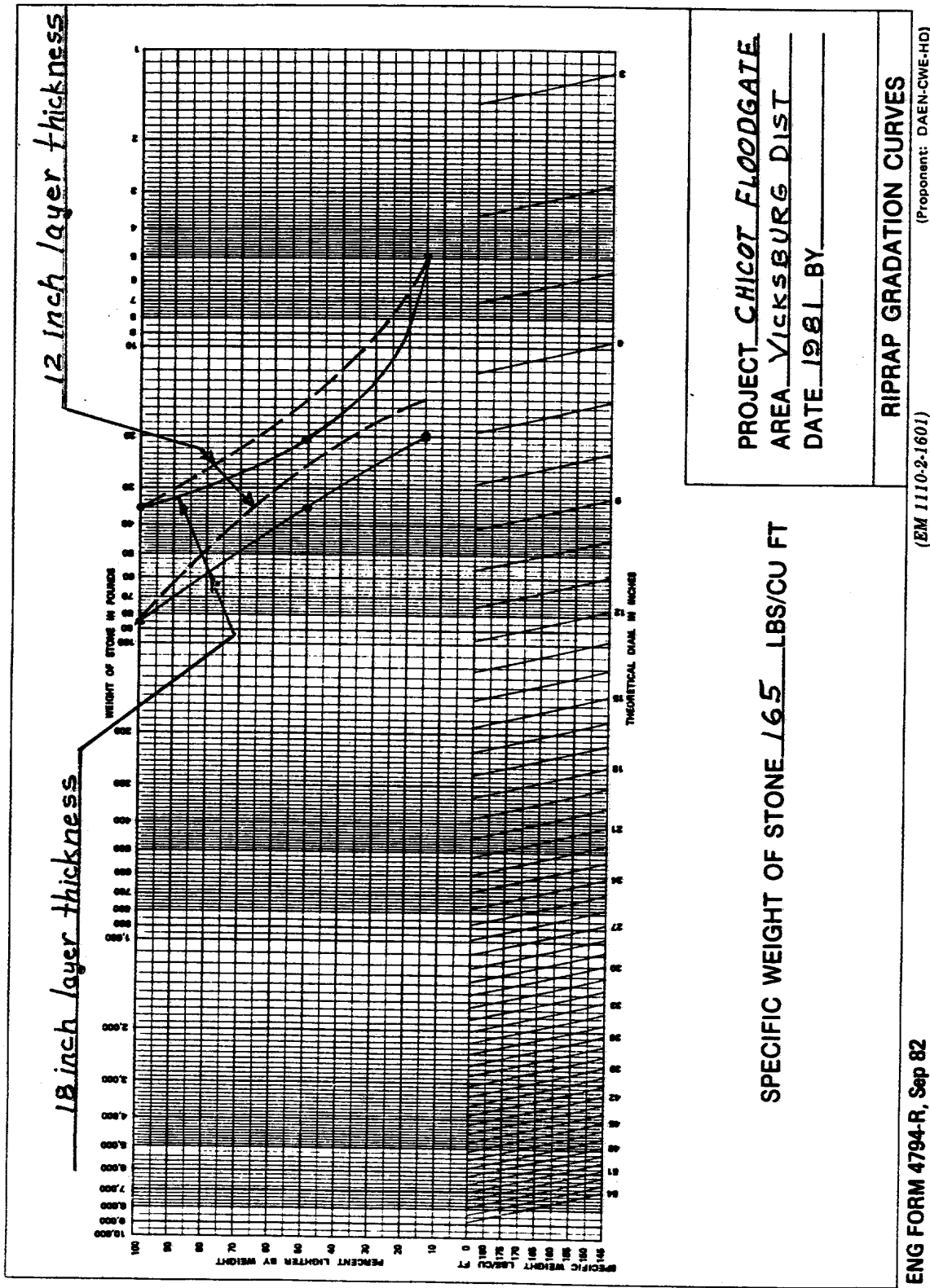
<sup>5</sup>Hydraulic Design of Rock Riprap, Miscellaneous Paper No. 2-777, dated February 1966

<sup>6</sup>Engineering Manual 1110-2-1602, dated 15 October 1980

AGC We know that design requirements on some special structures require different and special stone gradation from the normal A, B, and C. We have noticed an increase in the number of special gradations in the past year and believe that in some instances, one of the standard gradations would adequately serve. We request that special gradations be held to the minimum practicable and that standard gradation be used to the maximum extent possible.

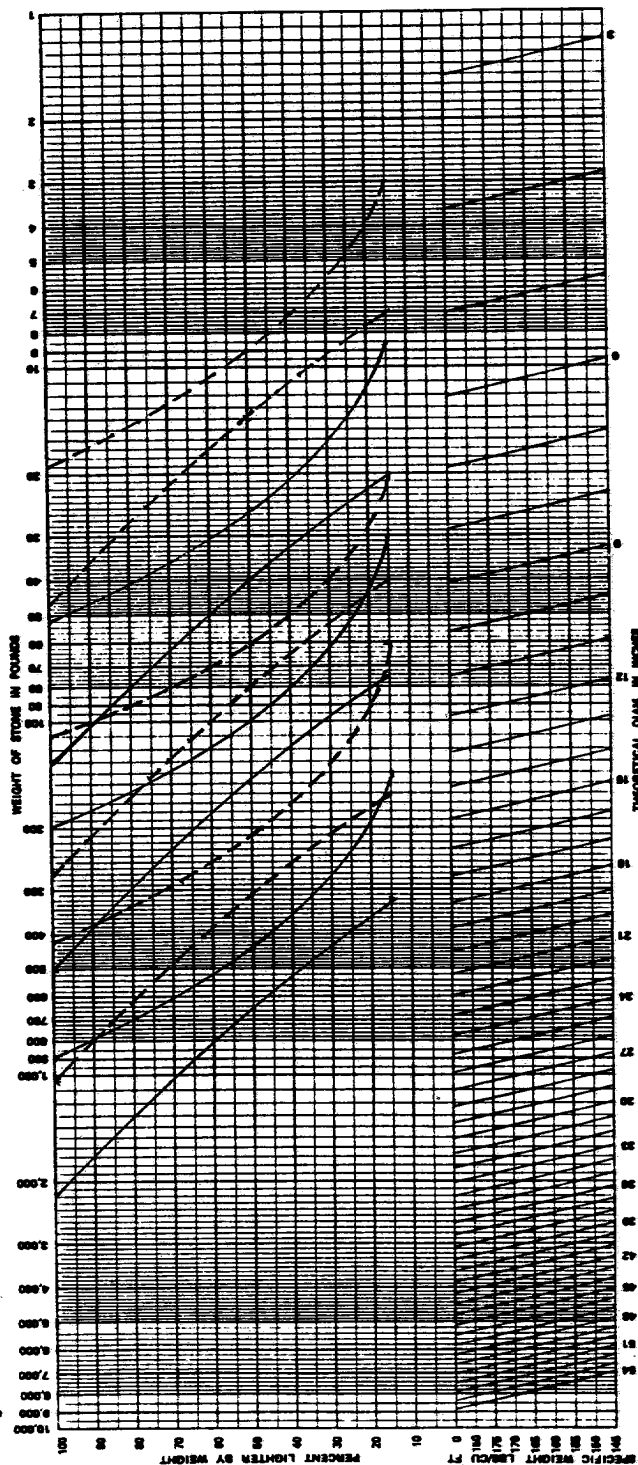
LMVD As you may recall, several years ago we preformed a study of stone sizes for use on the Mississippi River and navigable tributaries to help standardize stone gradations and facilitate procurement of stone. The resulting gradations are called graded stone A, B, and C and are primarily used in trenchfill revetments, protecting river banks, and for rock dikes. For protection at major flood control and navigation structures, the use of A, B, or C stones is not cost effective because these gradations allow too wide a range of stone sizes and allow a high percentage of fines which do not provide proper protection in areas of high velocity and turbulence which leads to riprap failure. Also, these gradations do not meet the Corps of Engineers criteria for stone gradation in such areas where high turbulence exists. At such structures a more uniformly graded stone is required. For example, the ratio of the weight of the largest size piece to that of the smaller pieces is in the neighborhood of 6, whereas that same ratio for Graded Stones A, B, and C is in the range of 70 to 200.

We recognize the desirability of developing standard gradations for riprap which can be used at structures, and we will undertake a study to do this. In this regard, it will be necessary for us to check with some quarries to determine the availability of stone sizes in the desired range in attempting to develop these new standard gradations. The cost effectiveness of using standard gradations will be evaluated. We will keep you informed of progress on this study.



set of gradation curves shown to Quarry Managers

Layer thickness = 54, 42, 33, 27, 21, 15 inches



$T = 1.5 D_{max}$  Max; 2.25 (1/50) Max

PROJECT STANDARD GRADATIONS

AREA LMVD

DATE 05/82 BY Malcolm Dove

SPECIFIC WEIGHT OF STONE 155 LBS/CU FT

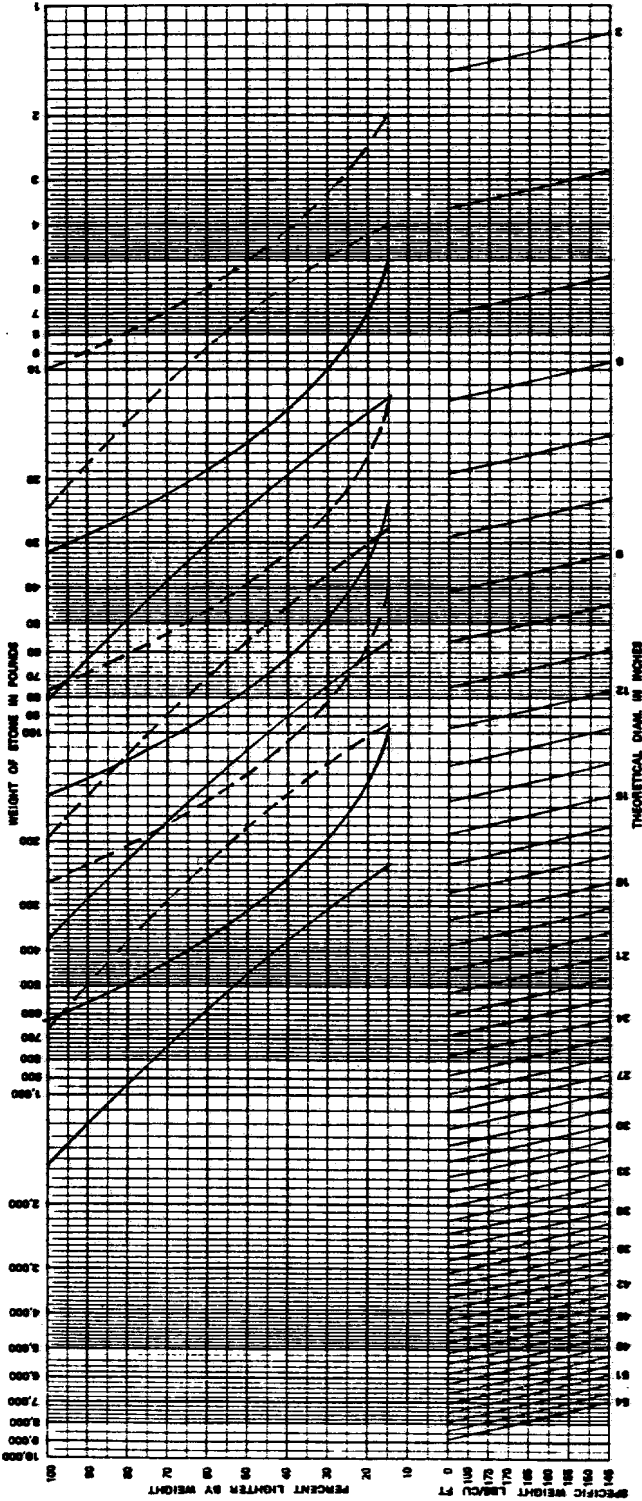
RIPRAP GRADATION CURVES

(EM 1110-2-1601) (Proponent: DAEN-CWE-HD)

ENG FORM 4794-R, Sep 82

*Set of gradation curves shown to Quarry Managers*

*Layer thickness = 48, 36, 30, 24, 18, 12 inches*



*T = 1.5 D(100) Max ; 2.25 D(50) Max*

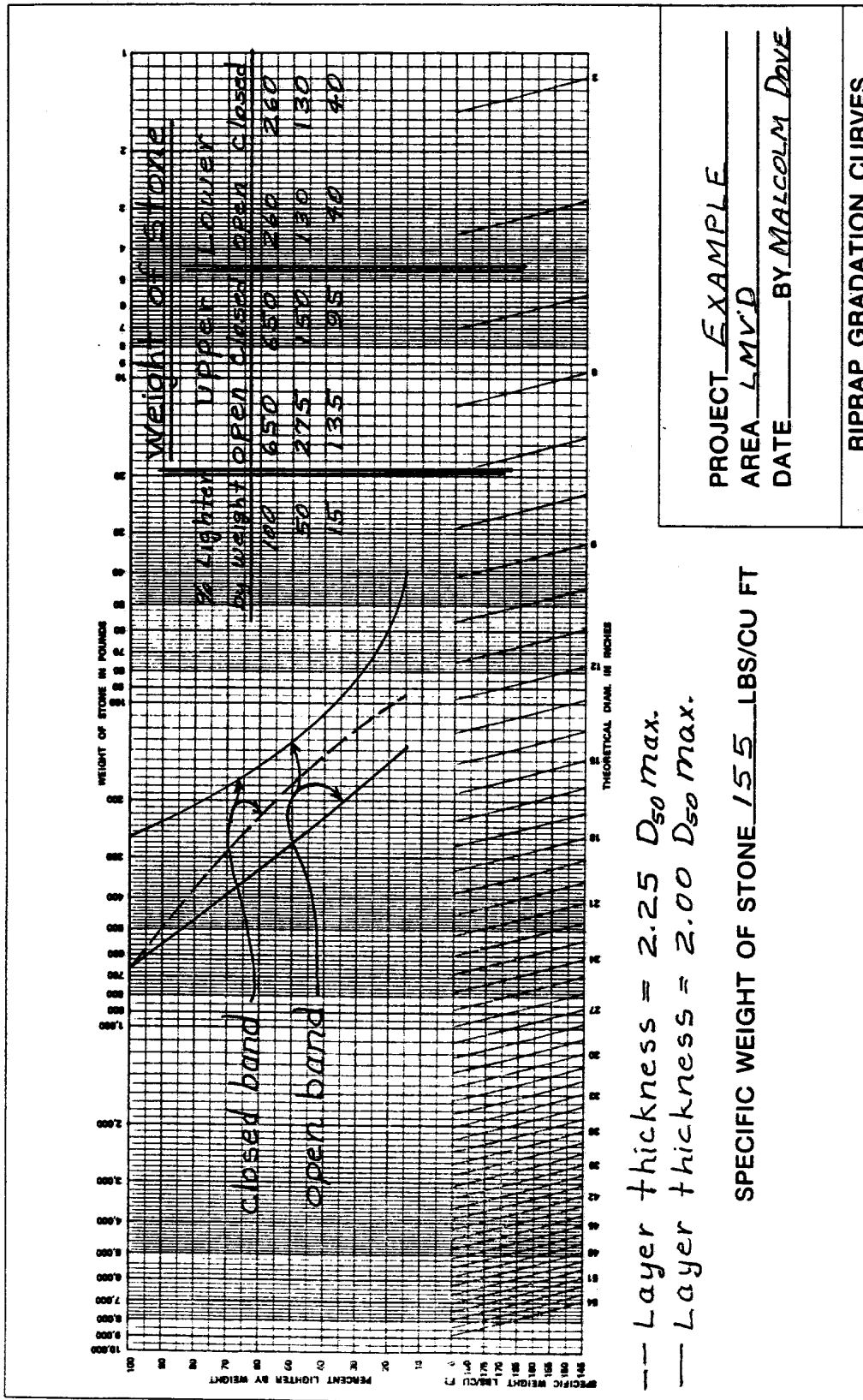
PROJECT STANDARD GRADATIONS  
AREA LMVD  
DATE Oct 82 BY Malcolm Dove

SPECIFIC WEIGHT OF STONE 155 LBS/CU FT

RIPRAP GRADATION CURVES

(EM 1110-2-1601) (Proponent: DAEN-CWE-HD)

ENG FORM 4794-R, Sep 82



-- Layer thickness = 2.25 D<sub>50</sub> max.  
— Layer thickness = 2.00 D<sub>50</sub> max.

SPECIFIC WEIGHT OF STONE 155 LBS/CU FT

\*

12 November 81

LWD

STANDARD NIPRAP GRADATIONS  
(Design Specific Weight 155 pounds per cubic feet)

	GRADATION NORMALLY PRODUCED MECHANICALLY								GRADATIONS NORMALLY REQUIRING SPECIAL HANDLING							
	12	15	18	21	24	30	36	42	48	54	63	72	81			
Layer Thickness in Inches High Turbulent Flow																
Layer Thickness in Inches Low Turbulent Flow			12	14	16	20	24	28	32	36	42	48	54			
Percent Lighter by Weight																
100	25 10	50 20	90 40	140 60	200 80	400 160	650 260	1000 400	1500 600	2200 900	3500 1400	5000 2000	7400 3000			
50	10 5	20 10	40 20	60 30	80 40	160 80	280 130	430 200	650 300	930 440	1500 700	2200 1000	3100 1500			
15	5 2	10 5	20 5	30 10	40 10	80 30	130 40	210 60	330 100	460 130	700 200	1100 300	1500 500			

\*